INTEGRATED CHEMICAL, RADIOLOGICAL AND BIOLOGICAL MONITORING FOR AN AUSTRALIAN URANIUM MINE – A BEST PRACTICE CASE STUDY

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ABSTRACT

The Australian Government's Supervising Scientist Division (SSD) is the entity responsible for the independent supervision, monitoring and audit of uranium mines in the Alligator Rivers Region (ARR) of Australia's Northern Territory. The Ranger uranium mine, one of the world's largest producers of uranium oxide (5,000 tpa or 10% of world production), is located here. The mine lease is surrounded by the World Heritage-listed Kakadu National Park and is situated only several kilometres upstream of the Ramsar-listed Magela Creek wetlands. This location imposes especially stringent requirements on water management and, in particular, on the extent of permissible impact on receiving waters downstream of the mine.

The objective of SSD's aquatic monitoring program, which is the focus of this paper, is to provide independent assurance to the Australian community that the aquatic environment remains protected from detrimental impacts from current and past uranium mining-associated activities in the ARR. The aquatic monitoring program is a best practice multiple lines of evidence approach comprising grab sampling for chemical and radiochemical analysis, continuous monitoring of pH, EC and turbidity, sentinel *in situ* toxicological monitoring, bioaccumulation (body burdens) of radionuclides in freshwater mussels and ecosystem biodiversity assessment.

The techniques and indicators used in the monitoring program satisfy two key requirements for environmental protection assessment: (i) the early detection of significant changes to minimise the potential for broader scale ecosystem impacts; and (ii) the use of biodiversity indicators to provide ongoing information about the status of the aquatic ecosystems so as to be able to distinguish any impacts of mining from the effects of other regional ecological stressors.

The past 25 years of independent monitoring conducted by the SSD has not shown any environmentally significant impact on the aquatic ecosystems downstream of the mine. Detailed radiochemical investigations have shown that the mine lease accounts for only a very small proportion of the ^{226}Ra found in downstream freshwater mussels.

Current work is focused on developing a water quality guidelines framework that addresses the dynamic nature of variation in water quality parameters as revealed by the continuous measurements of physicochemical parameters. In particular, the relevance of management guidelines derived from ecotoxicological testwork using chronic 3-6 day exposure periods to pulse exposures that may be only several hours in duration is being investigated.

1. INTRODUCTION

The Australian Government's Supervising Scientist Division (SSD) is responsible for the supervision, monitoring and audit of operating and former uranium mine sites in the Alligator Rivers Region (ARR) of Australia's Northern Territory (see www.environment.gov.au/ssd). The objective of SSD's monitoring program is to provide independent assurance to the Australian community that the environment remains protected from current and past mining-associated activities in the region.

The Ranger uranium mine, one of the world's largest producers of uranium oxide (5,000 tpa or 10% of world production), is located in the ARR, and is the only uranium mine currently operating in the region. The mine lease is surrounded by the World Heritage-listed, Kakadu National Park and is situated only several kilometres upstream of the Ramsar-listed Magela Creek wetlands (Figure 1). This location imposes especially stringent requirements on water management and, in particular, on the extent of permissible impact on receiving waters downstream of the mine.

The position of the Supervising Scientist has been in existence since the beginning of mining at Ranger in 1980. A major function has been to oversight an extensive program of research to develop best practice methodologies for monitoring and assessing the impact of uranium mining on water and air (transport pathways), soil and sediments, and on bushfoods that are consumed by the local indigenous people. It is the aquatic monitoring program that is the focus of this paper since, in the high annual rainfall (wet-dry) monsoonal tropics, the water pathway is a key potential transport route of contaminants from the mine site .

The values that are to be protected provide the starting point for defining what constitutes a best practice performance monitoring program. In the case of the Ranger mine, the key values for protection of the aquatic environment are defined by the environmental requirements for the operation:

- *Maintain the ecosystem health of the wetlands listed under the Ramsar Convention on Wetlands;*
- *Protect the health of Aboriginals and other members of the regional community; and*
- *Maintain the natural biological diversity of aquatic and terrestrial ecosystems of the Alligator Rivers Region.*

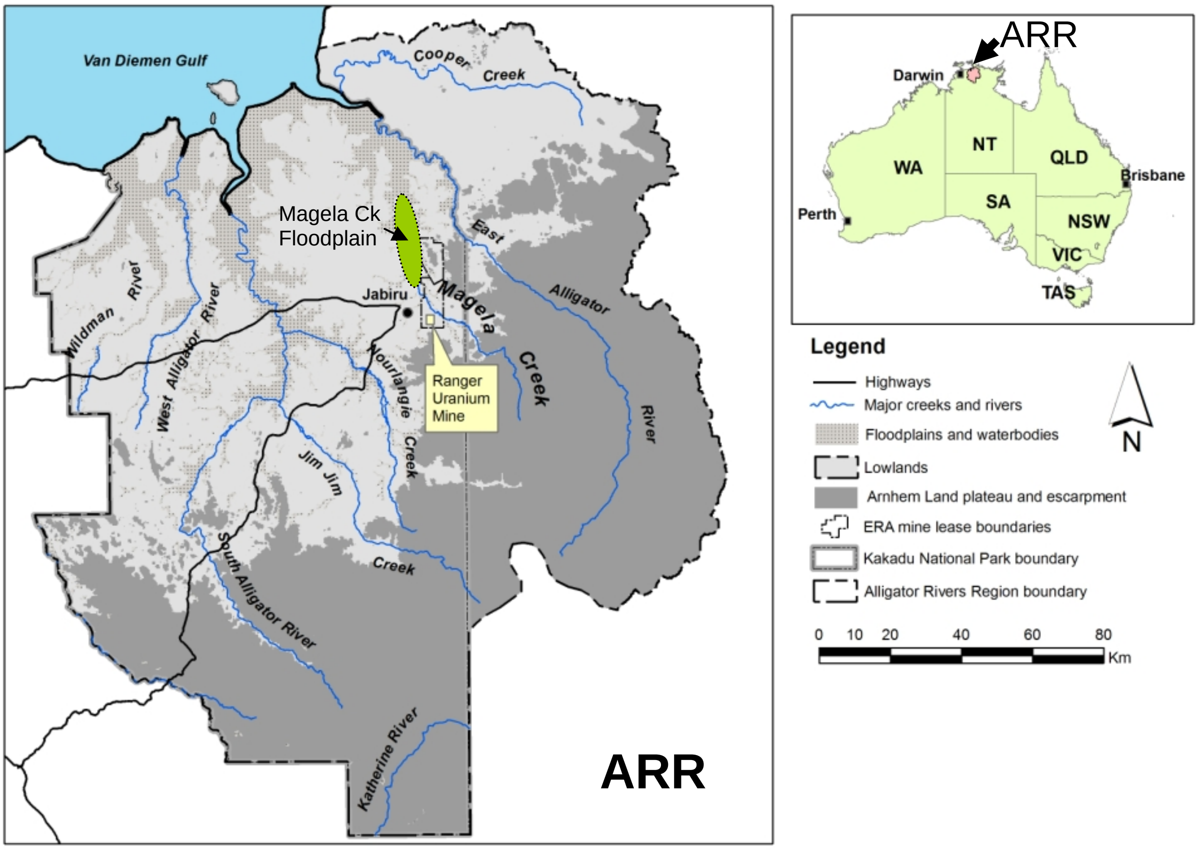

Figure 1. Location of the Alligator Rivers Region (ARR) and the Ranger Uranium Mine

The techniques and indicators used in the monitoring program satisfy two key requirements for best practice environmental protection assessment: (i) the early detection of significant changes to minimise the potential for broader scale ecosystem impacts; and (ii) the use of biodiversity indicators to provide ongoing information about the status of the aquatic ecosystems so as to be able to distinguish specific impacts of mining from the effects of regional (non-mining) ecological stressors. The monitoring methods used by the SSD are summarised below.

Early Detection of Changes:

- *Water physico-chemistry*
  - Grab samples for water quality measurements (weekly);
  - Multi-probe loggers for continuous measurement of water quality parameters with telemetry transmission to SSD headquarters (15 min frequency);
- *Ecotoxicity testing of key contaminants in minewater to derive site-specific water quality guidelines and to establish acceptable dilution ratios for mine site water prior to release to Magela Creek*
- *In situ toxicity monitoring using freshwater snails* (fortnightly);

Detection Over the Longer Term:

- *Bioaccumulation* – concentrations of metals and radionuclides in the tissues of freshwater mussels (annually).
- *Assessment of changes in biodiversity*
  - Benthic macroinvertebrate communities at stream sites (sampled at end of each wet season);
  - Fish communities in waterbodies (sampled at end of each wet season).

A major strength of SSD's aquatic monitoring program is its combination of physical, chemical and biological assessments which provides a multiple lines of evidence approach to assessing the effects of changes in water quality. Biological assessments integrate effects of past and present exposures and measure management goals directly, while water physico-chemistry provides information about the cause of any observed water quality changes (e.g. Batley et al 2003).

An additional level of complexity is provided by the bioaccumulation component that measures the accumulation of relevant metals and radionuclides in aquatic organisms consumed by the local indigenous people. The radionuclide data are required for the regional dose assessment model that is integrating all potential routes of radiological exposure to members of the public.

Communication of the results from the monitoring program is done in accordance with the concept of best practice. The monitoring data are regularly posted to SSD's website for access by the general public (www.environment.gov.au/ssd/monitoring/index); and the findings from the monitoring and research programs are communicated on a regular basis to the local indigenous people by a dedicated communications officer based at the SSD field station located near the mine site.

The rationale for, and key findings from, each of the components of the monitoring program are described and discussed below.

2. COMPONENTS OF WATER QUALITY MONITORING PROGRAM

Water Quality Grab Sampling

Water quality grab sampling at a set frequency is typically the starting position for a water quality monitoring program. SSD has been conducting a routine weekly program of grab sampling since 2001 to provide an independent check of the weekly grab sampling monitoring program run by Energy Resources of Australia (ERA) Ltd, the operator of the Ranger mine. The sampling sites are located upstream and downstream of the mine in Magela Creek, and upstream and downstream in Gulungul Creek, a right bank tributary of Magela Creek (Figure 2).

During the wet season months (typically late November to mid-April), mine-derived waters are passively released into Magela Creek via the Coonjimba Creek and Corridor Creek catchments, which include Coonjimba Billabong and Georgetown Billabong, respectively (Figure 2). These tributaries only connect with Magela Creek during the wet season months, at which time inputs of solutes come from surface runoff from waste rock dumps and low grade ore stockpiles located on the minesite.

Additional (non-point) sources include salts leached during the wet season from the footprints of land application areas to which minewater was applied during the preceding dry season. This water infiltrates the soil profile, and a proportion is flushed out during the next wet season.

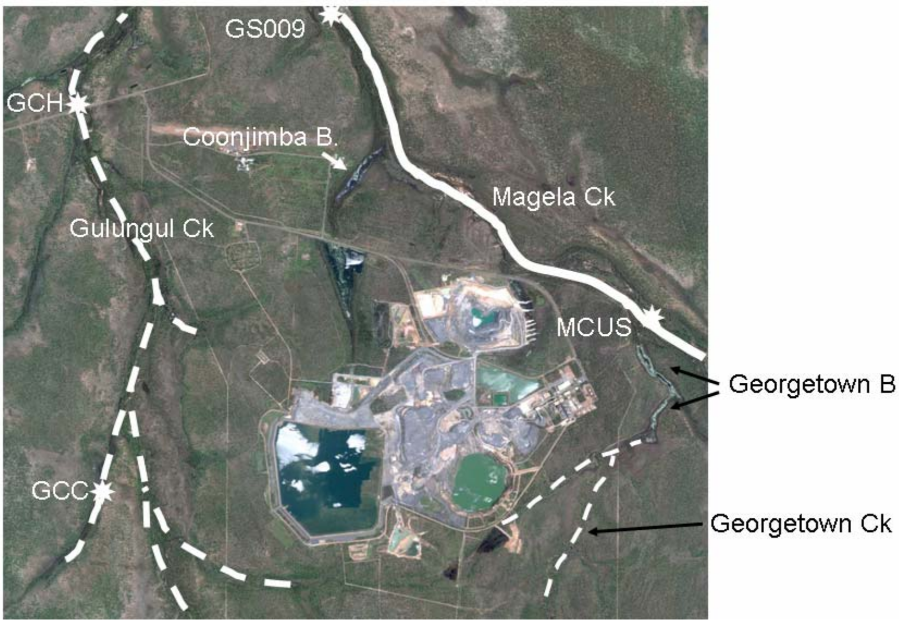

Figure 2. Locations of upstream and downstream water quality monitoring sites in Magela and Gulungul Creeks (marked by ✸). Billabongs are abbreviated as "B" – for example, Coonjimba B

The historical time series grab sample data have provided the basis for developing local water quality guideline values (detailed in Jones et al, 2006) for electrical conductivity and turbidity, derived according to the framework described in the Australian Water Quality Guidelines (ANZECC and ARMCANZ 2000). Water quality guideline values have been derived for Mg and U (the components of most potential concern in catchment runoff from the minesite) from the results of ecotoxicology testwork using at least five test species that represent a number of different taxonomic groups and trophic levels (Hogan et al 2005; van Dam et al, 2009).

The results from the weekly grab samples are compared with the guideline value for a given parameter to assess compliance.

A key assumption, of course, is that the one sample that is collected each week represents the water quality that prevailed throughout the week. In the case of Magela and Gulungul Creeks, both SSD and ERA sample at a weekly frequency. However, the times of sampling by each party are offset by about 48 h, thus providing a greater coverage than would be the case if only one entity was taking samples at a weekly frequency, or if both entities sampled at the same time. Nevertheless, there remained the question that was being asked by both regulators and community stakeholders as to whether weekly grab sampling was providing an accurate depiction of water quality variations in the receiving waters.

Continuous Monitoring of Water Quality

Commencing in the wet season of 2005/06, the SSD implemented a program of continuous monitoring for EC, pH and turbidity to rigorously assess, for the first time, the dynamic behaviour of these parameters and to test whether a weekly grab sample provides a reasonable indication of water quality over a timeframe of several days. During the wet season, the flow in Magela Creek varies over a large dynamic range (Figure 3) so, on this basis alone, it would be expected there would be substantial variation in the extent of dilution of solutes originating from the mine site. The continuous data records for EC for the upstream and downstream sites for the most recent 2008-09 wet season (November 08- April 09) are shown in Figure 4 and are similar to what has been observed in previous wet seasons.

Firstly, there is a minesite signature that becomes increasingly apparent as the wet season progresses, measured by the divergence between the upstream and downstream continuous and grab sample data. Secondly, the downstream trace for the continuous data shows many pulses of EC which vary substantially both in peak height and in duration. The driver of this pattern is the dynamic changes in flow ratios between the two minesite tributaries (Georgetown Creek and Coonjimba Creek) and Magela Creek that occur in response to differences in local and catchment wide rainfall patterns,. The weekly grab sample data for the downstream station do not adequately capture the dynamic range of EC resulting from the mine site derived inputs. In contrast, the continuous trace for the upstream (reference) site is very well described by the weekly grab data.

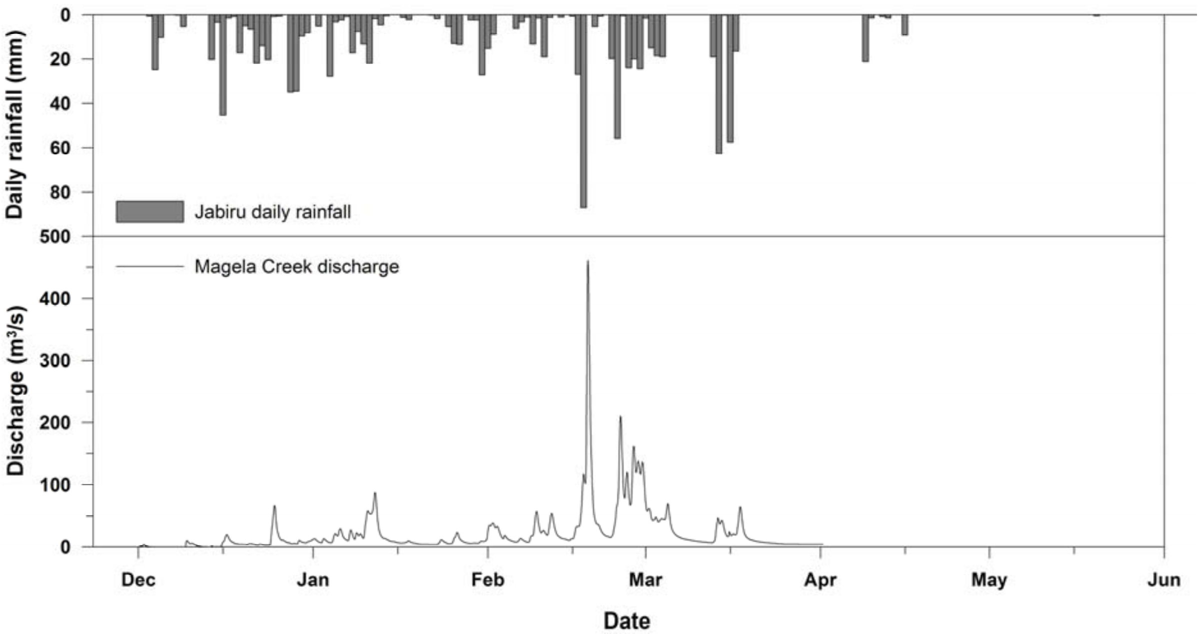

Figure 3. Magela Creek flow and local rainfall data for the 2008-09 wet season

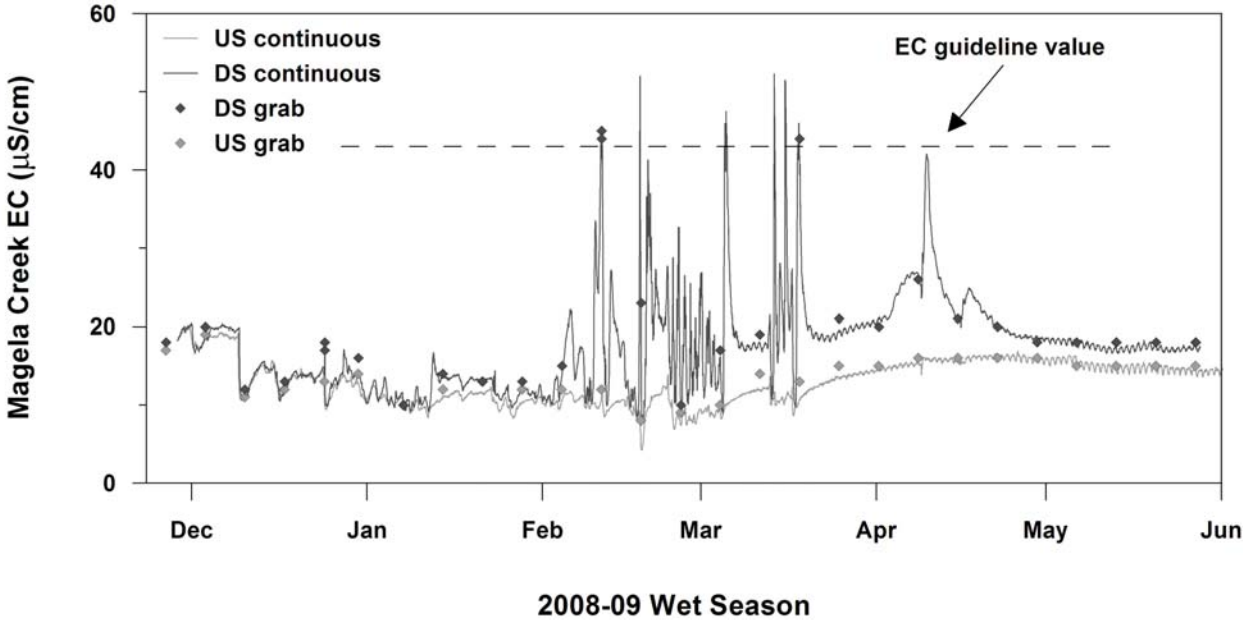

Figure 4. Continuous monitoring data for upstream and downstream stations with weekly grab sample values superimposed (as diamond symbols) for comparison

Superimposed on Figure 4 is the current water quality guideline value for EC that is applied for compliance screening, to place the EC data into context. There are only two instances of the weekly grab sample data exceeding this value during the 2008-09 season whereas there are many more (short duration) exceedances shown by the continuous data.

Whilst the use of continuous monitoring provides the ability to track general water quality parameters in real time, one of the key issues associated with the interpretation of the data, and its use for regulatory purposes, is the significance of short duration (pulse) exceedances of quality guidelines. Chronic exposure ecotoxicological test methods (employing exposure durations of days to weeks, depending on species) are most often used to derive benchmark water quality guidelines, so the effect of exposure duration needs to be implicitly addressed in a regulatory compliance framework based on continuous monitoring. The potential compliance and regulatory issues arising from the comparison of grab sample and continuous data in Figure 4 are being systematically addressed by a program of laboratory-based ecotoxicological testwork (described below).

Magnesium and sulfate are the major contributors to measured total EC in Magela Creek downstream of the minesite, and Mg is the dominant major cation in runoff from the site. Ecotoxicology studies have shown that in this very low EC environment, Mg is actually a significant potential toxicant (see van Dam et al, 2009, and below). In contrast sulfate is of only very low potential toxicity. Hence it was considered very important to determine if concentrations of Mg could be reliably inferred from the continuous EC record.

Several years of grab sample data have shown that there is an excellent correlation ($R^2 \approx 0.9$; $p < 0.001$) between EC and Mg over the range of measured EC values for each of the sites being monitored. The form of the correlation is location specific since the ionic composition of the water depends on the source (eg Magela Creek upstream, or Magela Creek downstream with composition influenced by Mg-rich minesite inputs). The datasets and correlation functions for Magela Creek upstream and downstream are shown in Figure 5. There is a linear relationship upstream and a slightly curvilinear (quadratic) relationship downstream.

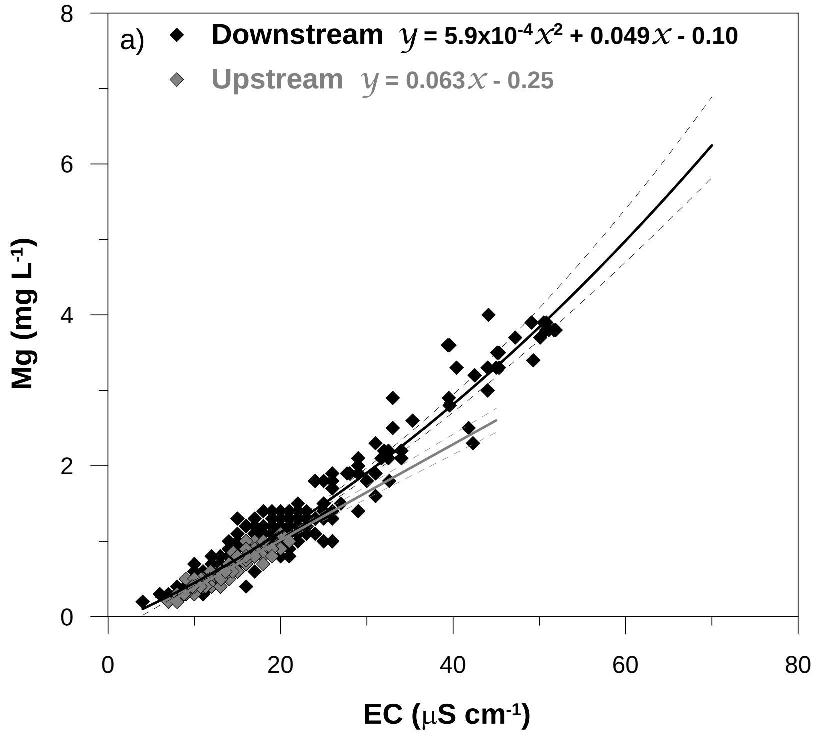

Figure 5. Relationships between Mg concentration and EC for the upstream ($R^2 = 0.86$, $P<0.0001$) and downstream ($R^2 = 0.94$, $P<0.0001$) sites in Magela Creek. The upper and lower 95% confidence limits are shown as dashed lines.

The slopes for the Magela Creek upstream and downstream sites are similar for periods of flow characterised by EC values of 0 to 20 µS/cm, during which periods the solute load is dominated by water from upstream. This condition can occur when there is little or no input from the minesite, or during flood flows where total load is dominated by solutes coming from upstream. For EC >20 µS/cm, the slope for the downstream site is higher, indicating a greater influence of Mg on EC compared to other solutes present, as is expected with input of Mg dominated mine waters. The existence of these two regimes at the downstream site is a result of variable mixing of upstream waters with mine waters and the resultant composite fit for the EC-Mg relationship is best described by a quadratic function.

The continuous EC data can be transformed to equivalent continuous Mg data Using the correlation functions. The Mg data are being used to estimate mine-derived loads of Mg (via the Mg-EC correlation, and flow record) in Magela Creek. This capability is proving especially useful for tracking the incremental and cumulative export of solutes from the minesite during the progress of a wet season (Supervising Scientist, 2008), and identifying their sources.

Water Quality Guidelines Derived from Ecotoxicology

The SSD ecotoxicology program is focussed on Mg and U, which are the two most important solutes in catchment runoff from the minesite. Whilst U has always been recognised as a potential toxicant in water quality monitoring programs worldwide, ecotoxicological testwork has shown that in the very low ionic strength (i.e. low EC, 10-20 µS/cm) conditions prevailing in the local waterways, Mg can be significantly toxic (van Dam et al 2009). A provisional 99% ecosystem protection trigger value (TV; sensu ANZECC and ARMCANZ 2000) of 2.5 mg/L has been derived from the species sensitivity distribution of six local aquatic species (van Dam et al in review). The finding that some local species were highly sensitive to Mg was significant since, prior to this work being done, Mg has typically been regarded as an innocuous solute at low concentrations. It suggests that low ionic strength receiving environments elsewhere, such as in parts of Scandanavia, Canada and south-east Asia, could be at increased risk from the Mg that is typically present at elevated concentrations in mine-derived water.

Converting continuous EC to equivalent Mg concentrations (as described above) makes it possible to compare the peak Mg concentrations with the water quality trigger value for Mg. When this is done, several peak values that exceed the provisional guideline value have been identified during each of the three wet seasons that the continuous monitoring system has been in place. However, the guideline value is based on a chronic (continuous) exposure over a typically 3-6 day period (depending on species), so the relevance of shorter duration pulse exposures that exceed this value needs to be implicitly determined. Statistical analysis of the continuous data obtained over the past four wet seasons reveals that exposure durations of mine water pulses in Magela Creek are typically in the order of hours, not days.

Consequently, an initial series of tests has been run with three of the suite of six test organisms, to quantitatively assess the effect of shorter duration pulse exposures (Supervising Scientist 2009). The organisms were exposed to one 4 hour pulse of Mg at the start of the four to six day test period. Under this pulse exposure regime, Mg was approximately half as toxic as the continuous exposure (IC50 ~ 700 mg/L Mg) for the green hydra, *Hydra viridissima*, and approximately an order of magnitude less toxic than the continuous exposure for the duckweed *Lemna aequinoctialis* and the cladoceran, *Moinodaphnia macleayi*. However, when the cladoceran was exposed to a 4 hour pulse at the onset of reproductive maturity (i.e. at age 27h; corresponding to 27-31 hours from the start of the test), Mg was found to be only two times, rather than 10 times less toxic than the continuous exposure, indicating that the timing of the pulse is a key factor for this species.

For all three species tested thus far, Mg pulse concentrations that exhibited toxic effects are well in excess of the maximum concentration (11 mg/L) thus far found in Magela Creek. Even in the most sensitive test, where *M. macleayi* was exposed at the onset of reproductive maturity, the concentration that caused a 10% inhibition of the test endpoint (IC10; generally considered an 'acceptable' level of effect), of 208 mg/L Mg, was still approximately 20 times higher than the reported maximum Mg concentration.

The findings from this work to date indicate that short duration pulse exposures that exceed the chronic guideline are of substantially lower adverse effect than would be seen in the event that a chronic exposure had occurred. However, the extent to which this is the case depends on the particular species and its life cycle. The ultimate objective of this work is to derive more environmentally relevant water quality TVs, that are better aligned with the actual behaviour of Mg in Magela Creek.

Biological Monitoring

In Situ Toxicity

In this type of monitoring, effects of discharges from the Ranger minesite on receiving waters are evaluated directly using responses of aquatic animals exposed to the creek water. . Reproduction (egg production) in freshwater snails, *Amerianna cumingi*, is measured, with each chronic exposure test running over a four-day exposure period (the same length of time as the chronic toxicity test method used in the laboratory). The snail egg production response measure is quite sensitive to both Mg and U, with laboratory-derived IC10 values of ~5 mg/L and ~15 µg/L, respectively. (Hogan et al in review; van Dam et al in review).

Test data for the snail bioassay method have been obtained over the past 18 years. Until the 2008/09 wet season the snails were deployed in tanks - located on the bank of Magela Creek - through which water was pumped (creekside monitoring). However, commencing in the most recent 2008/09 wet season, the *ex situ* creekside method was replaced by an *in situ* method (described in Supervising Scientist Report, 2008), whereby the capsules containing the snails are deployed in containers floating in the creek itself.

The differences between the upstream and downstream results (numbers of eggs) are plotted, through time, with typically 8 to 9 tests being conducted each wet season (ie every two weeks). If the difference values differ significantly from those arising from a previous period where no mining impacts have occurred, using an ANalysis Of VAriance (ANOVA) test, it may indicate a mine-related effect. Technical details of the statistical design and data analysis procedures may be found in Humphrey et al (1995).

Figure 6 shows the continuous EC data for the 2008-09 wet season in the top panel and the corresponding snail test results in the bottom panel. The snail tests were conducted both during times of very little input from the mine site (as evidenced by the close proximity of the upstream and downstream EC traces between December and the end of February) and the period between February and mid-March when there were several instances of pulses exceeding the downstream guideline value for EC (43 µS/cm = 3.3 mg/L Mg). There is no significant difference between the snail results for either of these periods, indicating lack of effect from the short duration pulses (of Mg). Indeed, for the entire 18 year period that this toxicity monitoring technique has been employed, no significant differences have been found between the upstream and downstream responses of the snails, indicating no detectable minesite impact by this measure (Supervising Scientist 2008).

Aquatic Biodiversity

This component of the biological monitoring program compares the abundance and diversity of macroinvertebrates and fishes in Magela Creek downstream of the Ranger mine with reference sites that are not impacted by mining activities. In this context it is important to have a number of reference sites so that natural seasonal and spatial (regional) changes can be distinguished from any mine-related impacts. In contrast to the tests with snails that are conducted through the wet season, the biodiversity assessments are done in the recessional flow period at the end of the wet season. The reason for sampling at this time is that it is considered to provide an integrated picture of the effects of the whole of the preceding wet season on abundance and diversity.

Macroinvertebrates

Macroinvertebrate communities have been sampled from a number of sites in Magela Creek during the recessional flow period at the end of the wet season each year from 1988 to the present. The design and methodology have been gradually refined over this period. The design is now a balanced one comprising upstream and downstream sites at two 'exposed' streams (Gulungul and Magela Creeks) and two control streams (Supervising Scientist 2008).

For each sampling occasion and for each pair of sites for a particular stream, dissimilarity indices are calculated. These indices are a measure of the extent to which macroinvertebrate communities of the two sites differ from one another. A value of 'zero' indicates macroinvertebrate communities identical in structure while a value of 'one' indicates totally dissimilar communities, sharing no common taxa. The results from these dissimilarity plots, multifactor ANOVA and multivariate ordination have shown no detectable impact of mining on the downstream macroinvertebrate communities.

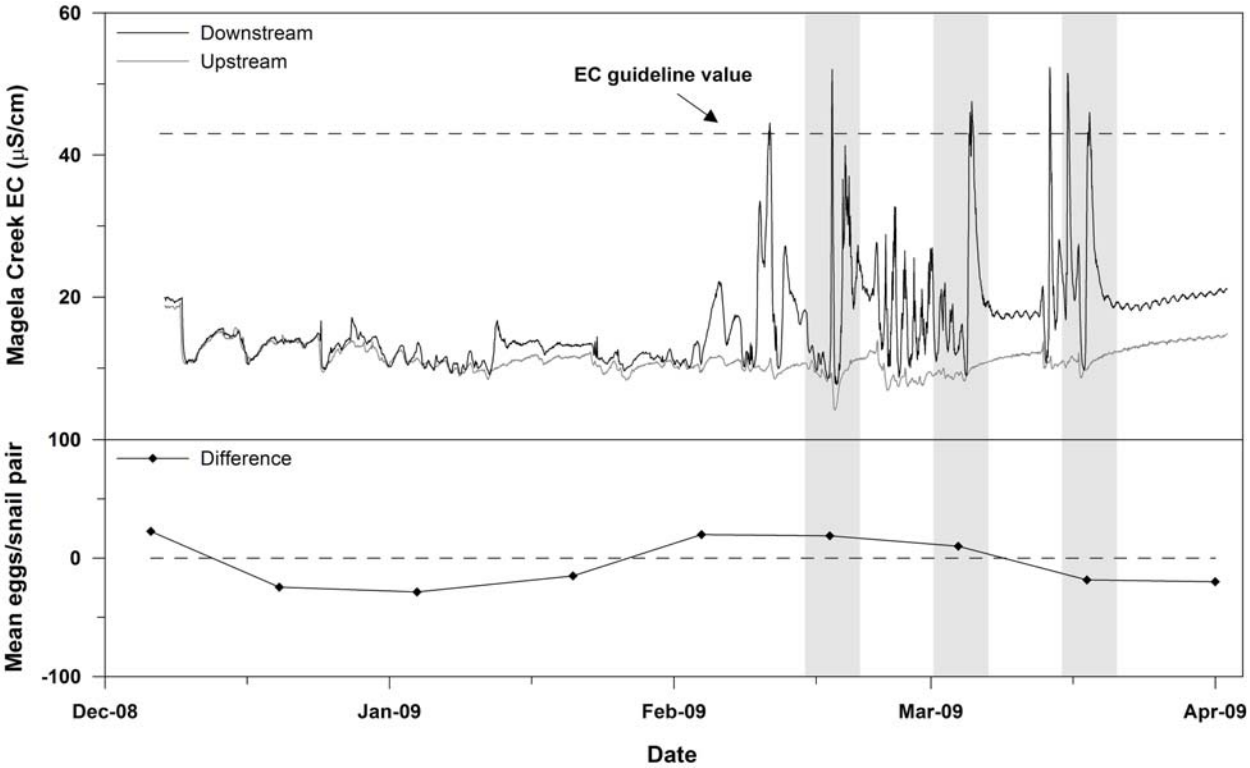

Figure 6. Comparison between continuous EC data (top panel) and snail test results (bottom panel). The snail test results are expressed as the difference between the numbers of upstream (control) and downstream (impact) egg masses. Vertical shaded bars indicate where an elevated pulse of EC occurred during the 4 day duration of a snail test.

Fish

Assessment of fish communities in billabongs is conducted between late April and July each sampling year, with the precise timing of sampling in any one year depending on when significant rain ceases.. Data are gathered using non-destructive observation methods, from ‘exposed’ and ‘control’ sites in deep channel billabongs annually, and from shallow, lowland billabongs every second year. Details of the methods are provided in the Supervising Scientist’s Annual Report for 2003–04 (Supervising Scientist, 2004).

For both deep channel and shallow lowland billabongs, comparisons are made between a billabong in Magela Creek downstream of the mine and a control billabong from a catchment not exposed to mining. The similarity of fish communities in exposed sites to those in control sites is determined using multivariate dissimilarity indices, calculated for each sampling occasion. The results from these measurements made since 1994 indicate no changes that could be attributed to inputs from the mine (Supervising Scientist, 2008).

Monitoring Radionuclides in Aquatic Organisms

An important component of the monitoring program for the Ranger mine measures uptake of radionuclides in freshwater mussels, *Velesunio angasi*. In contrast to the other components of the aquatic monitoring program which are focussed on protecting the health of the aquatic ecosystem, this aspect is focussed on the protection of human health.

Among the suite of radionuclides measured, radium-226 (^{226}Ra) is of particular interest as ^{226}Ra in mussels has been identified as the major contributor to the radiological dose from ingestion of bush foods by local indigenous people (Martin et al, 1998). This comparatively large contribution occurs because (a) freshwater mussels are an integral component of the diet of the Mudginberri community located 12 km downstream from the mine; (b) the high concentration factor of 19,000 for radium in freshwater mussels, and (c) the large dose conversion factor for ^{226}Ra of 0.28 $\mu Sv \cdot Bq^{-1}$.

The average committed effective doses calculated for a 10-year old child who eats 2 kg of mussel flesh per year, based upon average concentrations of ^{226}Ra and ^{210}Pb from Mudginberri Billabong mussels collected between 2000 and 2007, is approximately 0.2 mSv. Whilst the total annual committed effective dose from all pathways is less than the prevailing international dose limit of 1 mSv above background (ICRP 2007), consumption of the mussels comprises a dominant proportion of the total radiological dose to these people. Thus it is very important to know whether the minesite is a significant source of the ^{226}Ra, in the context of driving ongoing accumulation of this key radionuclide in mussel flesh.

A comprehensive investigation was undertaken recently to determine the extent to which the mine may be contributing ^{226}Ra to the mussels downstream (Brazier et al, 2009). This work involved collecting mussels, sediment and water along Magela Creek from well upstream of the mine down to Mudginberri Billabong, and analysing all samples for radium, uranium and stable lead isotope ratios.

A simple upstream-downstream comparison of radium activity concentrations in mussels is not an appropriate method to unambiguously detect a mine signal since variations in radium activity concentrations found in mussels along the catchment are the result of a range of factors unrelated to mining activity (eg mussel growth rates and body weights, competing chemistry during metal uptake, local geology), the precise contributions from which are yet to be fully understood. Activity and isotope ratios, respectively, are better suited for source identification.

Each mussel age class was measured for the radioisotopes of lead (^{210}Pb), thorium (^{228}Th) and radium (^{226}Ra & ^{228}Ra) by gamma spectrometry, and stable lead isotopes by inductively coupled plasma mass spectrometry. Measurement of the same isotopes were made on sediment and water samples (^{226}Ra only). ^{226}Ra and ^{228}Ra are members of the uranium and thorium decay series, respectively, and ^{206}Pb and ^{208}Pb are the respective stable end members. Hence the activity ratio of the two radium isotopes provides a measure of the relative contribution of uranium and thorium-rich sources, respectively, to the radium activity concentration in a sample. The lower the ^{228}Ra/^{226}Ra activity ratio in sediments or mussels, the higher is the contribution of radium derived from a uranium rich source. Similarly, the lower the ^{208}Pb/^{206}Pb isotope ratio the higher is the contribution of radiogenic lead derived from the decay of uranium.

This study has found that changes in ^{228}Ra/^{226}Ra activity and lead isotope ratios along Magela Creek are largely natural features of the catchment, rather than mining-related. In particular, the uranium concentrations in the mussels at all sites are comparable to pre-mining values from 1980; and the gradual increase of uraniferous signature in sediments and mussels along the creek channel implies a catchment-wide contribution rather than a contemporary mining-related impact. Overall, the results show that there is very little contribution from the minesite to the ^{226}Ra that is being accumulated by the mussels in Mudginberri Billabong.

3. CONCLUSIONS

This paper has described the components of the SSD's multiple lines of evidence best practice monitoring program for impacts on receiving waters of discharges from the Ranger uranium mine. Both leading edge (immediate water quality) and longer term (ecosystem level) indicators are addressed. The ecosystem level assessments are especially important because they can potentially detect any systemic longer term effects that may not be picked up by water quality analysis alone.

The value of continuous monitoring has been demonstrated. However, the availability of high time resolution data raises the challenge of how to accommodate short duration pulses in a management trigger framework that is based on water quality values derived from chronic (3-6 day) ecotoxicological tests. The results from an initial series of tests to compare the effect of a pulse exposure with a chronic exposure have been described. One of the important findings has been that the timing of exposure in the life cycle stage can be important, and this aspect will need to be accounted for in any framework (for example 24 or 72 hour data averaging) that seeks to more closely align pulse and chronic exposure time periods.

Overall the past 25 years of independent monitoring conducted by the SSD has not shown any environmentally significant impact on the aquatic ecosystems downstream of the mine. In addition, detailed radiochemical investigations have shown that the mine lease accounts for only a very small proportion of the ^{226}Ra found in downstream freshwater mussels, and hence only a very small component of the ingestion pathway by local indigenous people.

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